**TITLE**

# Temporal estimation in prediction motion tasks is biased by a moving destination

**RUNNING HEADER**

Prediction motion with moving destination

**AUTHORS & AFFILIATIONS**

Jonathan C. Flavell[1,2]; Brendan T. Barrett[1]; John G. Buckley[3]; Julie M. Harris[4]; Andrew J. Scally[5]; Nathan B. Beebe[1]; Alice G. Cruickshank[1]; Simon J. Bennett[6]

[1]University of Bradford, School of Optometry and Vision Science

[2]University of York, Department of Psychology

[3]University of Bradford, School of Engineering

[4]University of St Andrews, School of Psychology and Neuroscience

[5]University of Bradford, School of Health Studies

[6]Liverpool John Moores University, School of Sport and Exercise Science

**CORRESPONDING AUTHOR**

Brendan T. Barrett

B.T.Barrett@bradford.ac.uk

+44 (0) 1274235589

**ABSTRACT**

An ability to predict the time-to-contact (TTC) of moving objects that become momentarily hidden is advantageous in everyday life and could be particularly so in fast-ball sports. Prediction motion (PM) experiments have sought to test this ability using tasks where a disappearing target moves towards a stationary destination. Here, we developed two novel versions of the PM task in which the destination either moved away from (*Chase*) or towards (*Attract*) the moving target. The target and destination moved with different speeds such that collision occurred 750, 1000 or 1250ms after target occlusion. To determine if domain-specific experience conveys an advantage in PM tasks, we compared the performance of different sporting groups ranging from internationally competing athletes to non-sporting controls. There was no difference in performance between sporting groups and non-sporting controls but there were significant and independent effects on response error by target speed, destination speed and occlusion period. We simulated these findings using a revised version of the linear TTC model of response timing for PM tasks (Yakimoff et al. 1987, 1993) in which retinal input from the moving destination biases the internal representation of the occluded target. This revision closely reproduced the observed patterns of response error and thus describes a means by which the brain might estimate TTC when the target and destination are in motion.

**KEY WORDS**

prediction motion

motion extrapolation

coincidence timing

time-to-contact (TTC)

## INTRODUCTION

Whether estimating that it is safe to exit a busy road junction or judging when to strike/catch an approaching ball, it is not unusual for the target of interest to become momentarily occluded from the actor's view, for example by people or street furniture. Yet we anticipate that the target continues to move unseen and are able to internally represent the occluded trajectory. In the laboratory, our ability to do this has been examined using prediction motion (PM) tasks in which a target moves towards a fixed destination (usually a line perpendicular to the target's trajectory) before disappearing or passing behind an occluder (e.g. Rosenbaum 1975; Lyon and Waag 1995; De Lucia and Liddell 1998; Benguigui et al. 2003; Bennett et al. 2010b; Bosco et al. 2015). The participant's task is typically to provide a response (usually via a button press) to indicate when the now invisible target would have reached its destination.

It has been suggested that performance in PM tasks is influenced by imposed oculomotor strategies (Bennett et al. 2010a; Makin and Poliakoff 2011), characteristics of target motion such as velocity (Sokolov and Pavlova 2003; Baurès et al. 2010, 2011; Bennett et al. 2010a; Zago et al. 2010; Baurès and Hecht 2011; Nakamoto et al. 2015) and the duration of target occlusion before it strikes the line (Peterken et al. 1991; Baurès et al. 2010). Other factors known to influence performance during PM tasks include the duration of visible motion (Sokolov and Pavlova 2003), the target size (Sokolov and Pavlova 2003; Battaglini et al. 2013), the presence of background texture (De Lucia et al. 2000; Battaglini et al. 2014), motion after-effects (Gilden et al. 1995; Battaglini et al. 2014), stimulus-to-background contrast (Battaglini et al. 2013) and the presence of visual distractors (Lyon and Waag 1995). In addition, prior experience of fast-interceptive tasks has been shown to influence PM performance. For example, expert baseball players mis-locate suddenly disappearing targets (traversing left to right on a computer screen) as significantly further ahead than novice players (Nakamoto et al. 2015). It was suggested that this overestimation was the result of the experts' enhanced capability for motion prediction and that such domain-specific expertise may be advantageous in compensating for neural transmission and processing delays as well as for transient loss of visual information (e.g., from saccades, blinks or target occlusion).

In the present study, we created two novel extensions of the PM task to explore how participants respond when both the target and the destination to which it is moving are in motion. In the first experiment (*Chase*), the destination retreated from the target as it was approached, whereas in the second experiment (*Attract*) the destination and target moved towards one another. Importantly, the *Chase* and *Attract* experiments differ from those of previous studies that examined simultaneous motion prediction of two occluded targets as they approached a fixed visible destination (e.g. Oberfeld & Hecht, 2008; Baurès et al., 2011). Rather than generating two time-to-contact estimates (TTC, the period from occlusion to the instant of contact) and preparing two motor responses that are influenced by a psychological refractory period, here the *Chase* and *Attract* tasks required a single estimate of TTC based on the relative motion between an occluded and a visible object.

As in typical PM tasks where a target moves toward a stationary destination, we expected to find, for both *Chase* and *Attract*, changes in response times as target speed and occlusion period were varied (e.g. Peterken et al. (1991), Baurès et al. (2010, 2011), Bennett et al. (2010a), Zago et al. (2010), Baurès and Hecht (2011), & Nakamoto et al. (2015)). Moreover, here we also sought to determine whether having a continuously visible moving destination biases the estimation of target speed during occlusion. In addition, we examined if performance in these novel PM tasks is influenced by expertise in ball sports (i.e. domain-specific expertise). To this end, we compared male and female non-sporting controls to athletes who may sometimes have to predict visible and occluded motion.

# METHODS

## Participants

Members of the Huddersfield Giants Rugby League football club (all male, n = 19), the Leeds/Bradford Marylebone Cricket Club University squad (all male, n = 24), the England's national women's cricket team (n = 16) and male (n = 29) and female controls (n = 20) participated. Controls were students at the University of Bradford who had never played ball sports at a competitive level and were not routinely engaged in ball sports. Not all participants were included in the analysis for each experiment due to the data in some trials being unsuitable for analysis because of being erroneous or unrealistic (trial exclusion criteria are detailed below in 'Data acquisition, processing and analysis'). Participation numbers following data exclusion are provided in Table 1. Protocols were approved by the Committee for Ethics in Research at the University of Bradford and were in accord with the tenets of the Declaration of Helsinki. Participants gave written informed consent and reported normal or corrected to normal vision and no known neurological or sensorimotor deficits.

Table 1 For each experiment the number of participants per group (mean ± standard deviation) following removal of unsuitable data.

| | *Chase* (n = 97) | | *Attract* (n = 101) | |
|---|---|---|---|---|
| Group | n | Age | n | age |
| 1 - Male controls | 25 | 23.88 ± 5.1 | 27 | 23.63 ± 5 |
| 2 - Female controls | 19 | 22.47 ± 4.1 | 16 | 23 ± 4.2 |
| 3 - Male rugby | 17 | 23 ± 3.9 | 19 | 23.05 ± 4 |
| 4 - Male cricket | 21 | 20.67 ± 1.5 | 23 | 20.78 ± 1.5 |
| 5 - Female cricket | 15 | 25.4 ± 2.7 | 16 | 25.63 ± 2.8 |

## Experimental set-up

Participants sat in a darkened room facing a 20” (12×16” or 33.90×44.23° of visual angle) Sony Trinitron GDM-F520 CRT monitor. An adjustable chin-rest ensured the head was stationary and that the centre of the screen was 50 cm away and parallel to the eyes. A custom-made response key was positioned on a table between the participant and the screen. Participants were seated with arms relaxed and their forearms resting on the table. A PC (Dell Latitude E6530, Intel (R) Core (TM) i7-3540, 3 GHz CPU, 4GB RAM, 32 bit Windows 7) presented stimuli at a mean refresh rate of 85 Hz and spatial resolution of 1600x1400 pixels using custom scripts and Psychtoolbox (version 3.0.11 (Brainard 1997; Pelli 1997; Kleiner et al. 2007) operating within Matlab (R2014a The MathWorks Inc., Massachusetts, USA).

**Task and stimuli**

The participant's task in both experiments was to press the response key with the index finger of their dominant hand (determined using the Edinburgh Handedness Inventory; Oldfield, 1971) when the leading edge of a horizontally moving circular target was judged to collide with a vertical line (the destination) that was oriented perpendicular to the target's trajectory. Each participant completed *Chase* then *Attract* on the same day. Figure 1 shows the chronology of trials in both experiments. The visual appearance of stimuli was identical in each experiment and included a cue (white circle of radius 1 mm or 0.11°), a target (black circle of radius ~5 mm or .57°) with a white circle at its centre (radius 1 mm or .11°), and a destination (black line of 1 mm in width (0.11°) and 230 mm in length (24.7°)). The target and destination were located midway between the top and bottom of the screen, and were presented against a grey screen background. The display whites, greys and blacks had luminance of 65.1, 10.63 and 0.01 candelas/$m^2$, respectively. The black arrows in Figure 1 represent the direction in which the target and line (destination) were moving and the dashed white circle represents the unseen position of the target when its leading edge would have contacted the destination. Neither the arrows nor dashed circle were visible to the participant.

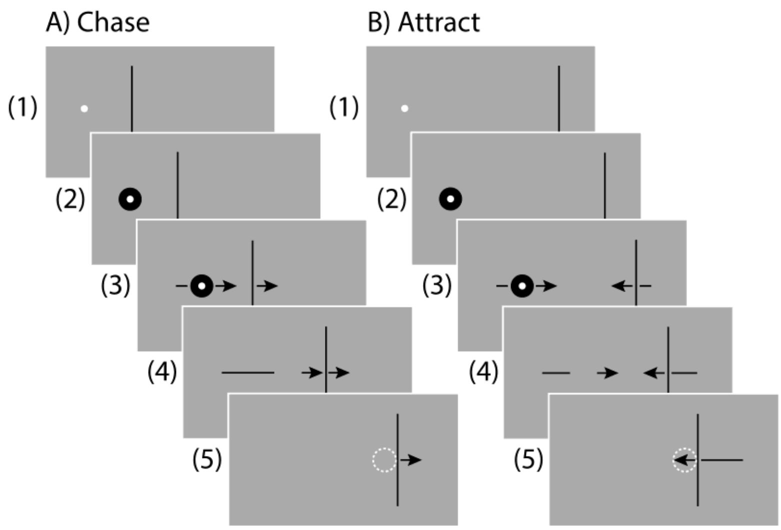


Figure 1 Schematic showing the trial chronology in *Chase* (A), and *Attract* (B).

The start of a trial was identical in both experiments: a stationary cue appeared to the left of the screen (Figure 1-*AB* panel 1), and the participant pressed the response key to begin. Pressing the key simultaneously replaced the cue with the target and caused the destination to appear some way to the target's right (Figure 1-*AB* panel 2). The target and line remained stationary for a random period between 500 to 1500 ms. Target and line behaviour differed between the experiments from this point on. In *Chase*, the target and the destination began to move rightwards (Figure 1-*A*, panel 3), whereas in *Attract* the target began to move rightwards whilst the destination began to move leftwards (i.e. they moved towards one another, Figure 1-*B*, panel 3). Target and destination movements always had linear, horizontal trajectories of constant speed (see Table 2). The target disappeared 500 ms after movement onset (i.e. there was always 500 ms during which target movement was visible) but the destination remained visible throughout the trial (Figure 1-*AB* panel 4). Participants were tasked with pressing the response key at the time when they estimated the now non-visible target would have collided with the destination (Figure 1-*AB* panel 5). A trial ended when the response key was pressed, and was followed by a new trial being presented 1000 ms later. By altering the horizontal starting locations of the target and destination, the target occlusion period was either 750, 1000 or 1250 ms. The target and the destination were no closer than 12 mm or 1.4° to the edge of the screen at the start of a trial, or at the moment of collision giving a maximum possible image rendering area of 281 mm, or 31.37° wide. The horizontal starting positions of the target and the destination were randomly jittered between trials to discourage estimation of contact time based on the initial position of stimuli rather than on the observed movement. For both the *Chase* and *Attract* experiments, participants completed five repetitions for each speed condition and occlusion period combination to yield 90 trials each in experiment (6 speed conditions × 3 occlusion periods × 5 repetitions). Condition order was randomised for each participant in both experiments. No feedback on response accuracy was given for any practice or experimental trials, and participants were not instructed where to look on the screen. Neither eye movements nor eye position were recorded.

Table 2 Target speed (TS) and destination speed (DS) in °/s for each experiment.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Chase* | TS: | 15 | 20 | 20 | 25 | 25 | 25 |
| | DS: | 10 | 10 | 15 | 10 | 15 | 20 |
| *Attract* | TS: | 10 | 10 | 10 | 15 | 15 | 20 |
| | DS: | 10 | 15 | 20 | 10 | 15 | 10 |

Before beginning the experimental phase, participants completed a practice block of 'classic' PM trials (target movement towards a stationary destination) to familiarise themselves with the apparatus and general task requirements (a full description is available in Supplementary Material). Next, they were given an explanation of the upcoming experiment and performed eight practice trials (randomly chosen from the possible conditions though without repetition of any condition).

**Data acquisition, processing and analysis**

Matlab (version R2014a) was used for data acquisition and post-experiment processing and analysis. The response key was sampled at the instant of each screen image refresh (i.e. at 85 Hz). Response error was calculated as the difference between actual contact time (of target and destination) and the instant at which the response key was pressed. The sign and magnitude of the error indicates how early (negative error) or late (positive error) a response was made. Outlying response errors were excluded using a negative cut-off of (*total travel time*/*2* × *-1*) and a positive cut-off of (*total travel time* – *view time*; note that view time was always 500 ms). For example, in the 750 ms occlusion condition, the target's total travel time was 1250 ms (750 ms occluded motion + 500 ms visible motion), giving a negative cut-off of -625 ms and a positive cut-off of 750 ms. Response errors which fell outside this range were excluded because they were seen as erroneous (or implausible) responses. Any participant with 3 or more of the 5 trials excluded for any given condition in a *Chase* or *Attract* (e.g. *Chase*: occlusion period of 750 and speed condition of 15|10) was removed from the data set for that task (i.e. from *Chase* or *Attract*). This resulted in the exclusion of 11 of 108 (10.2 %) participants from *Chase* and 7 of 108 (6.5%) participants from *Attract*. A fuller description of data exclusion rates is provided in Supplementary Material.

## Statistical analysis

Response errors were analysed via random effects regression modelling (StataCorp LP, College Station, TX, USA). This is an iterative process that is tolerant of missing data and attempts to find the simplest model that only includes terms with significant effects (i.e. terms which affect the data). Terms were incorporated sequentially, with their statistical significance determined using the likelihood ratio test, and provisionally retained if they returned *p*-values of 0.1 or less. Because of the iterative nature, only terms in the final model at $p \leq 0.005$ were deemed meaningful. The following terms and their interactions were explored via the above modelling approach: target speed (3 levels); destination speed (3 levels); occlusion period (3 levels); and group (5 levels).

# RESULTS

## *Chase*: Target moves towards a retreating line

Observation of box and whisker plots (Figure 2-*A*) of response errors for each speed condition and occlusion period indicated several patterns in the data. Across all conditions, responses[(1)] occurred: (1) less late and/or increasingly early as the occlusion period increased; (2) less early and/or increasingly late as the target speed increased whilst destination speed was held constant (e.g., 15|10 to 20|10 to 25|10, and 20|15 to 25|15); and (3) less late and/or increasingly early as destination speed increased whilst target speed was held constant (e.g., 20|10 to 20|15 and 25|10 to 25|15 to 25|20).

Regression modelling indicated that response errors were unaffected by group ($p$ = .44) but were significantly affected by occlusion period, target speed, destination speed, and by their interactions ($p < .001$) with the exception of the target speed × destination speed interaction. However, the proportion of the overall variance that was explained by the model when including both main and interaction terms ($r^2 = 0.282$) was only marginally greater than when including only main terms ($r^2 = 0.276$). Hence, we accepted the simpler (main terms only) model ($p < .001$, Table 3). Coefficients indicate that responses occurred less late and/or increasingly early as the occlusion period increased and as destination speed increased, but that responses occurred less early and/or increasingly late as the target speed increased (as suggested by Figure 2-*A*).

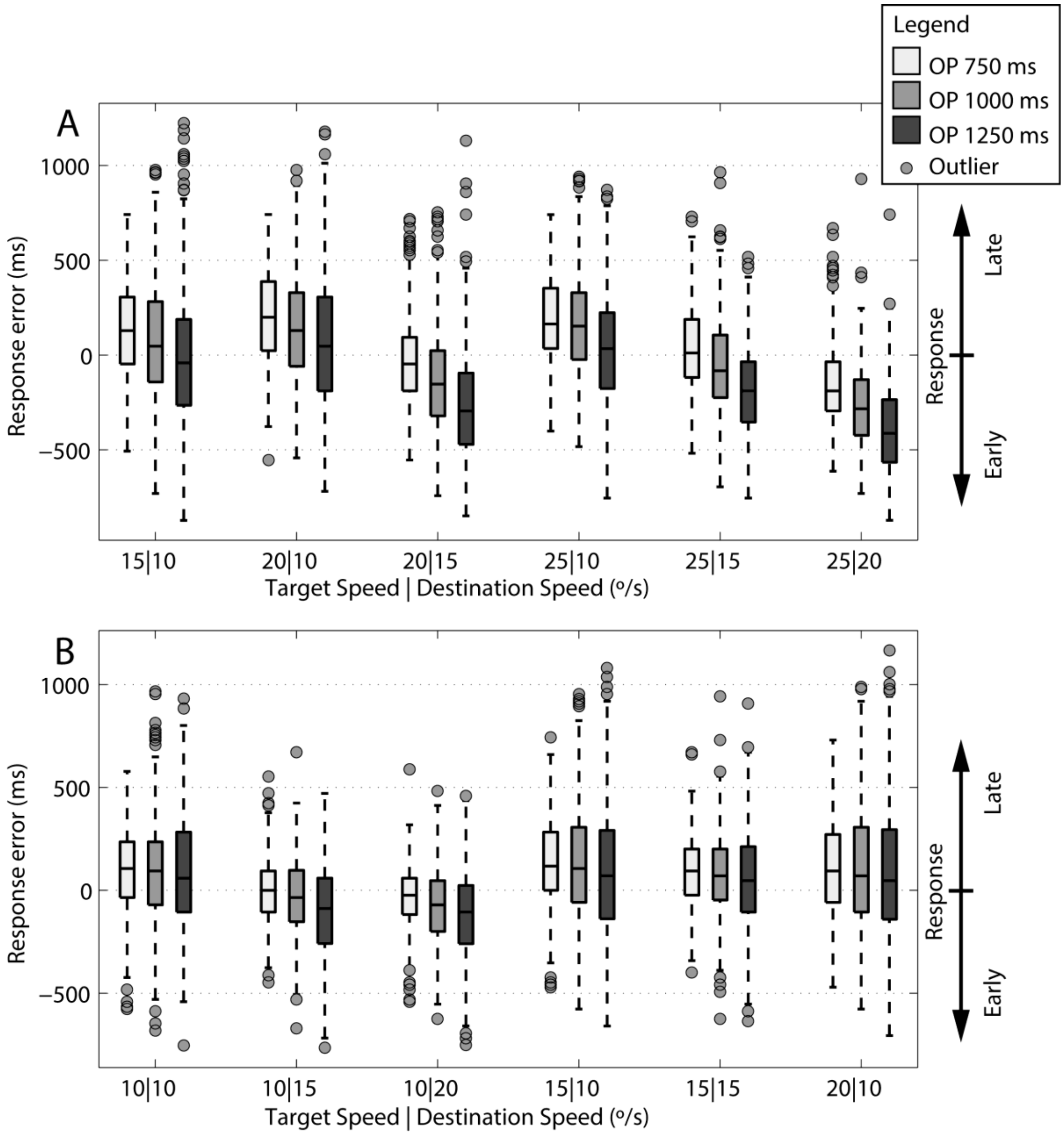

Figure 2 Box and whisker plots of raw response errors including median (central line), 25th and 75th percentiles (box edges), range of data (whiskers) and outliers (dots) for (A) the *Chase* experiment, and (B) the *Attract* experiment. Data are split by speed condition and occlusion period (OP; 750 ms = pale grey, 1000 ms = grey and 1250 ms = dark grey). Positive errors indicate late responses (responses after the target would have struck the line) and negative errors indicate early responses (responses before the target would have struck the line). For each combination of speed condition and OP, the percentage of trials considered outliers in these plots was between 0 and 2.52 % in *Chase*, and between 0 and 2.39 % in *Attract*.

Table 3 *Chase* experiment: Output of random effects regression model. Occlusion period (OP), target speed (TS) and destination speed (DS) were treated as covariates rather than factors because linear relationships were found between these terms and response errors.

Overall $r^2$ = .276
$\chi^2$ (3) = 5547.92
$p > \chi^2$ = < .001

| | Coefficient | Std. Error | Z | $p > z$ | 95% Confidence Intervals Lower | Upper |
|---|---|---|---|---|---|---|
| OP | -390.211 | 11.212 | -34.8 | < .001 | -412.186 | -368.237 |
| TS | 7.593 | 0.71 | 10.69 | < .001 | 6.2 | 8.985 |
| DS | -43.893 | 0.71 | -61.86 | < .001 | -45.283 | -42.502 |
| constant | 788.68 | 22.123 | 35.65 | < .001 | 745.319 | 832.041 |

***Attract*: Target and line approach one another**

Observation of box and whisker plots (Figure 2-*B*) of response errors for each speed condition and occlusion period indicates two patterns in the data. Across all conditions, responses occurred: (1) less late and/or increasingly early as occlusion period increased; and (2) less late and/or increasingly early as destination speed increased (whilst target speed was held constant e.g. conditions 10|10 to 10|15 to 10|20, and 15|10 to 15|15). The effects of alterations in target speed were inconsistent and appeared to depend on accompanying destination speed. For example, for the slowest destination speed (10 °/s) there appeared to be no change in response errors as target speed increased (e.g., 10|10, 15|10 and 20|10) but for the middle destination speed (15 °/s) the response errors indicated that responses occurred less early and/or increasingly late as target speed increased (e.g., 10|15 and 15|15).

Regression modelling indicated that response errors were unaffected by group ($p$ = .231) but were significantly affected by target speed, destination speed and occlusion period and their interactions ($p$ < .001). However, the proportion of the overall variance in the data that was explained by the model when including both main and interaction terms (overall $r^2$ = 0.101) was again only marginally greater than when including only main terms (overall $r^2$ = 0.1). Hence, we accepted the simpler (main terms only) model ($p$ < .001, Table 4). Coefficients for the main effects indicate that responses occurred less late and/or increasingly earlier as destination speed increased and as occlusion period increased. They also indicate a non-linear effect of target speed whereby an increase in target speed from 10 °/s to 15 °/s led to a greater change in response errors (+ 73 ms per °/s change in target speed) than an increase in target speed from 10 °/s to 20 °/s (+ 38 ms per °/s change in target speed).

Table 4 *Attract* experiment: Output of random effects regression model. Occlusion period (OP) and destination speed (DS) and were treated as covariates rather than factors because linear relationships were found between these terms and response error. Target speed (TS) was treated as a factor.

Overall $r^2$ = .1
$\chi^2$ (4) = 1604.29
$p > \chi^2$ = < .001

| | | | | | 95% Confidence Intervals | |
|---|---|---|---|---|---|---|
| | Coefficient | Std. Error | Z | $p$ > z | Lower | Upper |
| OP | -96.825 | 9.51 | -10.18 | < .001 | -115.464 | -78.186 |
| TS 15°/s | 72.565 | 4.589 | 15.82 | < .001 | 63.573 | 81.556 |
| TS 20°/s | 37.872 | 6.267 | 6.04 | < .001 | 25.59 | 50.156 |
| DS | -15.442 | .601 | -25.71 | < .001 | -16.619 | -14.265 |
| Constant | 314.529 | 18.444 | 17.05 | < .001 | 278.38 | 350.678 |

**DISCUSSION**

Much of current understanding regarding the ability to internally represent and predict target motion is informed by work using the prediction motion (PM) task (Peterken et al. 1991; Lyon and Waag 1995; De Lucia and Liddell 1998; Benguigui et al. 2003; Bennett et al. 2010b; Bosco et al. 2015). Typically, the PM task requires a participant to estimate time-to-contact (TTC) of a target that moves at a particular speed and then becomes occluded or disappears as it approaches a fixed destination. Accordingly, it has been suggested that participants could estimate TTC based on information available prior to target occlusion (see De Lucia and Liddell, 1998). Here, we conducted two novel variations of the PM task in which optimal performance required participants to take account of information from both a moving target and a moving destination. Specifically, we investigated the ability to estimate TTC of a target at a destination that was either retreating from a target (*Chase*) or approaching it (*Attract*). Given the previously reported influence of prior experience on PM performance (Nakamoto et al. 2015), we also sought to determine if temporal estimation in these novel tasks differed as a function of expertise in ball sports (i.e. domain-specific expertise). To summarise our results, we found that in both *Chase* and *Attract* tasks, response errors did not vary by sporting expertise. However, there were independent influences of target speed, destination speed, and occlusion period. To aid interpretation of these findings, we present a revision to the linear model of response timing in traditional PM tasks (i.e. moving target and stationary destination) proposed by Yakimoff et al. (1987, 1993). This revision closely reproduces the pattern of response errors observed in our experimental data where both the target and destination are in motion. Key to this is replication of the bias in the internal representation of target speed (and thus estimated TTC) by retinal input from the observed moving destination.

**Modelling TTC estimation**

In prediction motion experiments where the target moves toward a stationary destination (Peterken et al. 1991; Baurès et al. 2010) it is common to find that participants respond earlier as occlusion period increases. Yakimoff et al. (1987, 1993) proposed that this occurs in part because participants overestimate target speed. They suggested response times can be modelled as:

(Equation 1) $$T_r = \alpha * T_c + \theta$$

where $T_r$ is the response time, $T_c$ is the actual time-to-contact (TTC), $\alpha$ is a constant representing the magnitude of overestimation of target speed and $\theta$ is a constant representing the sum of participant's internal delays (visual, neural, mechanical etc.).

Using the general concept that relative speed of a target that approaches a destination is misestimated during occlusion in PM tasks (see also Lyon and Waag, 1995; Makin et al., 2008), we sought to simulate the observed pattern of response errors in the *Chase* and *Attract* tasks. Importantly, in our experiments visual input from the moving target was available for only the first 500 ms of a trial, whereas visual input from the destination was available throughout. Assuming that participants solve the PM task using some form of motion extrapolation, rather than a counting strategy (DeLucia & Liddell, 1998), the implication is that participants need to generate and remember an estimate of target speed early in the trial, whereas they can continually update their estimate of destination speed throughout the trial. Accordingly, we considered whether the patterns in our data could be described by a revision to the linear model of response timing in PM tasks proposed by Yakimoff and colleagues. Specifically, we considered whether the remembered target speed was influenced by the continuously present destination speed. In other words, could the moving destination bias the internal representation of the now unseen target motion?

First, we included terms that reflect the participants' perception of target and destination speed when they are visible:

(Equation 2a) $pTS = TS * \gamma$

(Equation 2b) $pDS = DS * \gamma$

where $pTS$ and $pDS$ are the perceived speed of the target and destination respectively, $TS$ is the target speed, $DS$ is the destination speed, and $\gamma$ is a constant representing the magnitude of speed misestimation. At this stage, we assume that misestimation of TS and DS is minimal and hence $\gamma$ is set to 1. However, this constant could change to reflect the presence of a background (e.g., coarse vs. sparse) or eye movement condition (i.e., fixation vs. pursuit).

Next, we characterised participants' estimation of target speed when there is a bias induced by the continuously visible moving destination:

(Equation 3) $eTS = (pTS * \alpha) - (((pTS * \alpha) - pDS) * \beta)$

where $eTS$ is the participant's estimate of target speed, $\alpha$ is a constant representing a misestimate of target speed following target occlusion, and $\beta$ is a constant representing the magnitude of the influence of $pDS$.

To estimate the relative speed ($eRS$) of the target and the destination, and to account for direction of travel in *Chase* and *Attract*, we used the following:

(Equation 4a) $Chase\ eRS = eTS - pDS$

(Equation 4a) $Attract\ eRS = eTS + pDS$

With values of $\gamma = 1$, $\alpha = 1.3$, and $\beta = 0.2$, we generated an estimate of the relative speed between the moving target and destination. This was then expressed relative to the actual relative speed (*aRS*) to give a measure of the misestimation ($\alpha_{rv}$) during occlusion as shown in Equation 1.

Having also estimated the constant $\theta$ in Equation 1 (i.e., sum of participant's internal delays) for each speed condition in *Chase* and *Attract* as the intercept in a linear regression of actual median TTC (response error + occlusion period) against occlusion period, we resolved a revised version of the linear model thus:

(Equation 5) $T_r = \alpha_{rv} * OP + \theta$

where *OP* (the occlusion period in *Chase* and *Attract*) takes the place of $T_c$ from Equation 1.

Finally, we estimated participants' response errors in *Chase* and *Attract* by subtracting our simulated $T_r$ from the occlusion period. As can be seen by comparing the data shown in Figure 2 and Figure 3, we were able to reproduce response errors with both magnitude and sign that were a close match to the actual response errors observed in *Chase* and *Attract.* We did not test exhaustive variations of $\alpha$ and $\beta$ in Equation 3, such as might be expected for individual participants, or allow the value of $\gamma$ to stray from 1. Our goal was simply to demonstrate that, with the chosen values, our revised version of Yakimoff and colleagues' linear model was able to provide a reasonable description of the pattern of response errors in our *Chase* and *Attract* experiments.

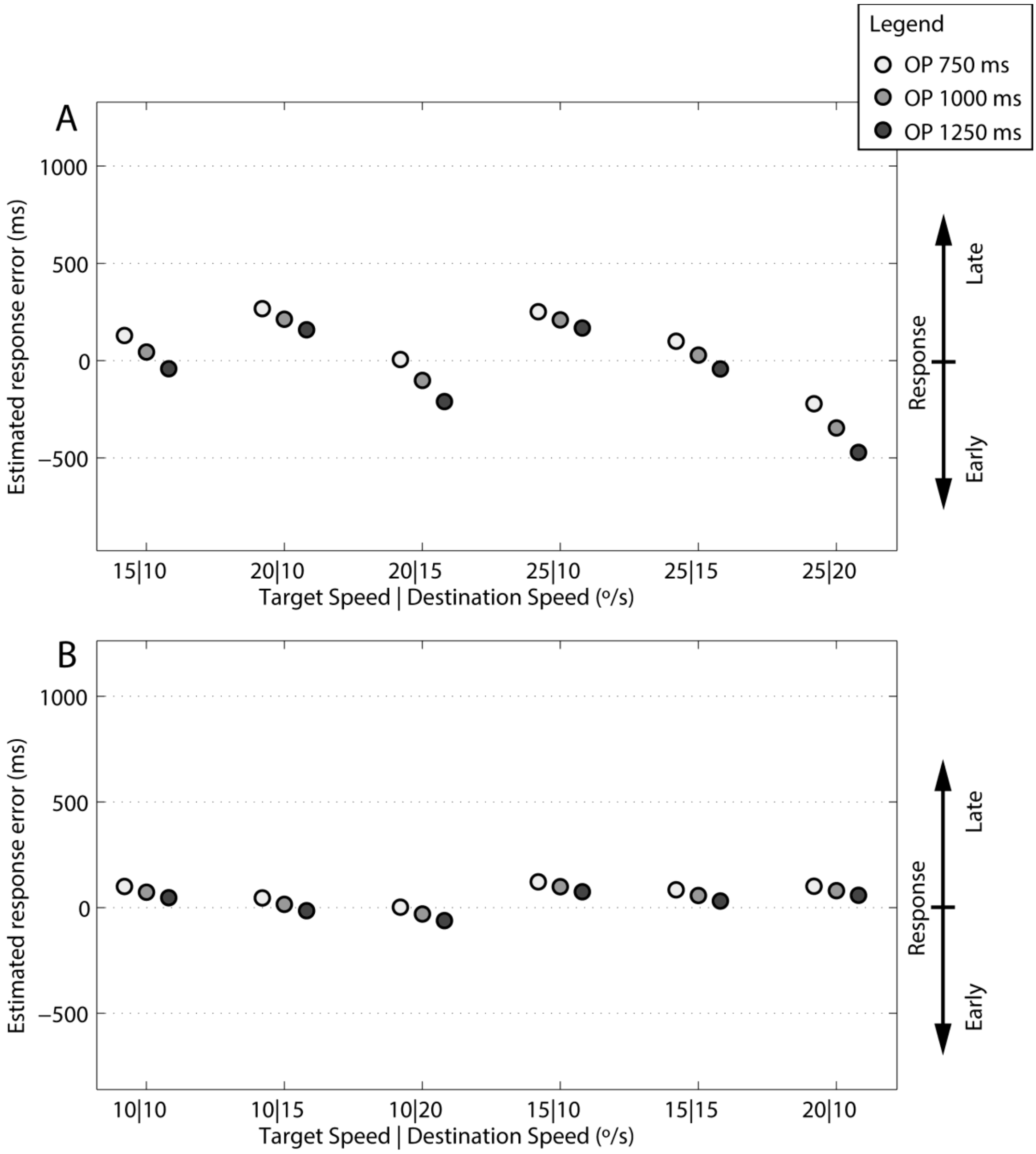


Figure 3 Modelled estimates of response errors split by speed condition and occlusion period (OP; 750 ms = pale grey, 1000 ms = grey and 1250 ms = dark grey). (*A*) *Chase* experiment. (*B*) *Attract* experiment. Estimates were generated using Equations 2, 3, 4 and 5 with $\gamma = 1$, $\alpha = 1.3$ and $\beta = 0.2$.

**Non-linear effects of target speed in *Attract***

For the *Attract* experiment, there was a non-linear effect of target speed whereby response errors increased (i.e. responses were made later) more when target speed increased from 10 to

15 °/s (+73 ms) than when target speed increased from 10 to 20 °/s (+38 ms) (Table 4). Note that because target speed was treated as a factor in our statistical modelling (due to the non-linear effect) we do not have the comparison of response error change as target speed increase from 15 to 20 °/s. This non-linear effect was replicated by our model, thus suggesting it was a result of the experimental conditions tested. Why might this be the case? Equation 3 reveals that there is a greater bias of estimated target speed when the target speed is 20 °/s compared to when it is 15 °/s. This is because, in these conditions, the difference between destination speed and target speed is greater when the target speed is 20 °/s (speed condition 20|10 = Δ10) than when it is 15 °/s (speed condition 15|10 and 15|15 = Δ5 and Δ0, respectively). This means that the magnitude of overestimation of target speed is lower when the target speed is 20 °/s than in both speed conditions where target speed is 15 °/s (see Figure 4, dark grey dots). In other words, the unequal balancing of target and destination speeds created unequal bias on estimated target speed, which ultimately resulted in an apparent non-linear effect of target speed on response errors. In Figure 4 we also present model predictions for the overestimation of target speed for two conditions that were not tested in the *Attract* task. It is clear that when the difference between the target and destination speeds is the same within speed conditions (e.g. 15|10 to 20|15 and 15|15 to 20|20), target speed is overestimated to a greater extent in the higher target speed conditions. Our model predicts that had we tested these speed conditions in *Attract*, we could have expected linear effects of target speed on response errors (as found in *Chase*).

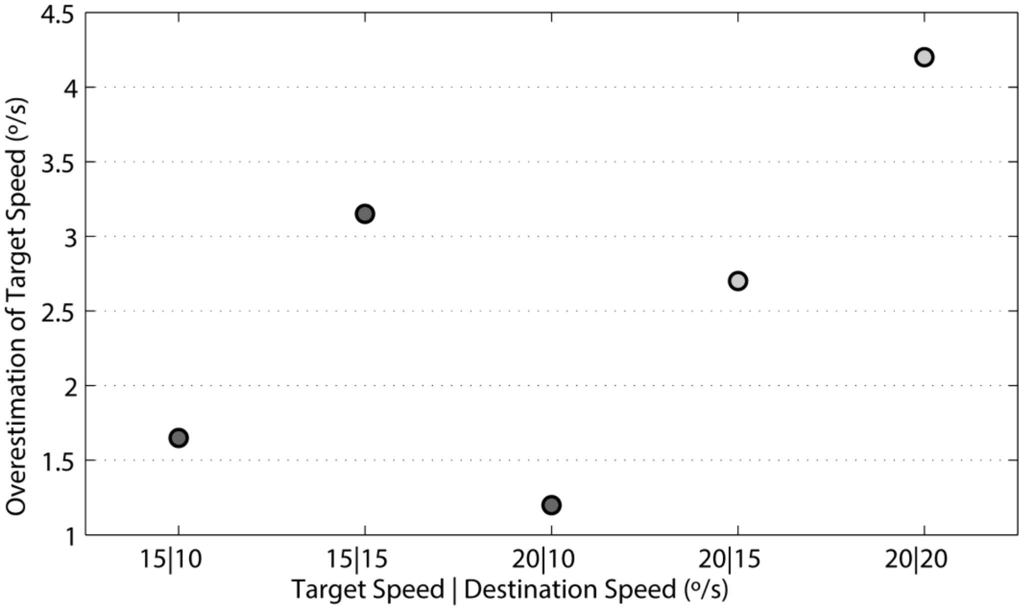


Figure 4 Overestimates of target speed in 3 tested conditions from *Attract* (dark grey dots) and 3 untested potential conditions for *Attract* (light grey dots). The overestimate is the estimated target speed (eTS from Equation 3) minus actual target speed.

## Difference in destination speed effect between *Chase* and *Attract*

The magnitude of the destination speed effect was approximately three times greater in *Chase* (-44 ms, Table 4) than in *Attract* (-15 ms, Table 5). The bias of destination speed on estimated target speed, predicted by our model, goes some way to explain this effect. In *Chase*, the destination speed is always less than the target speed, so there is always a negative bias. However, in *Attract* the destination speed can be less than, greater than or equal to the target speed, so the bias can be negative, zero or positive. If this is the source of the magnitude difference between *Chase* and *Attract*, then running the *Attract* experiment with an extended range of speed conditions (perhaps additionally testing 15|20, 20|15 and 20|20) should deliver a similar magnitude of destination speed effect as we found in *Chase*.

## Comparison of 15|10 and 20|10 speed conditions between *Chase* and *Attract*

We have proposed that the bias of target speed by destination speed occurs in the same way for both *Chase* and *Attract* (Equation 3). One might assume, therefore, that response errors should not differ between *Chase* and *Attract* when the speed conditions are comparable (i.e.

in the 15|10 and 20|10 speed conditions that appeared in both tasks). However, it is critical to remember that our model incorporates the relative speed for each task (i.e., '*eTS - pDS'* in *Chase; 'eTS + pDS'* in *Attract*), and thereby accounts for the direction of travel of both the target and destination. This results in different estimated response errors for each task even when the speed conditions are comparable. In other words, although 15|10 and 20|10 speed conditions were used in both tasks, it is only the magnitude of the speeds that were comparable because the destination's direction of the travel was different in each task.

**No effect of sporting expertise**

There are situations where sporting expertise appears to convey an advantage in predicting an object's future motion. For instance, Nakamoto et al. (2015) studied representational momentum (RM), a phenomenon where people judge an occluded moving target as being further along its path than it actually is. They found that expert baseball players exhibited greater RM than novices. The authors suggest that this may be advantageous in fast-ball sports because it could alleviate information processing delays and aid interception or avoidance of occluded targets. In the present study we found no influence of sports expertise in any of our PM tasks (i.e., there was no indication that motion prediction in sporting elites differed to that in controls, $p >= 0.231$). Why might this be case? Nakamoto et al. intended their task to simulate baseball pitching and as such used high-speed targets (10 or 15 m/s) with short presentation and occlusion times (133 ms occlusion time in both cases). They found expert/novice differences only in the highest speed condition where novices' TTC estimation were poorer. It is possible that the advantage exhibited by elite baseball players in Nakamoto et al. (2015) was related to greater reliance on anticipatory processes operating during the initial viewing period rather than improved extrapolation of an occluded trajectory. Such anticipation requirements were not a feature of the tasks used the present study. Indeed, while motion prediction is a general visuo-motor ability that is exercised by all, 'advanced' anticipatory processes may only be present in sub-populations who experience situations where such abilities are conducive to their goals.

**Study limitations**

All participants completed *Chase* before *Attract*, and thus we cannot rule out the possibility of experiment order effects. However, it is relevant to note that participants never received feedback on the magnitude or direction of response errors, so there is no obvious reason why performance would change in any meaningful or systematic way following exposure to certain conditions. Also, our proposed model, which does not include any attempt to incorporate order effects, produced reasonable estimations of participants' response errors in both the *Chase* and *Attract* tasks. Therefore, it seems likely that any unaccounted effect of task and/or condition order would have had a negligible influence on the observed pattern of results. This could be confirmed in a future study that combines conditions of the *Chase* and *Attract* tasks into a single experiment with randomised trial order.

**Summary**

Extending upon the classic prediction motion task, we determined response errors in two novel prediction motion tasks in which the target's destination could move either away from (*Chase*) or towards an approaching target (*Attract*). We found that, irrespective of participants' experience of playing sport, response errors became less late and/or increasingly early as occlusion period or destination speed increased, and increasing early as target speed increased. We presented a revision of Yakimoff and colleagues' (1987, 1993) linear model of response timing in PM tasks, which closely reproduced the pattern of response errors observed in our experimental data. Future work could perhaps consider other ways in which our results (or results from tasks like *Chase* and *Attract*) may be modelled, and what biological mechanisms may underlie TTC judgements in these tasks.

**ACKNOWLEDGEMENTS**

This study was funded by the Biotechnology and Biological Sciences Research Council (grant references BB/J018163/1, BB/J016365/1 and BB/J018872/1). The authors declare that they have no conflict of interest. Special thanks for participating go to the England and Wales Cricket Board, the England Women's cricket team, the Leeds/Bradford MCCU, and the Huddersfield Giants Rugby League Football Club. Desney Richards (Technical Director of Research Solutions) produced the button box used in these experiments.

## REFERENCES


**Battaglini L**, **Campana G**, **Camilleri R**, **Casco C**. Probing the involvement of the earliest levels of cortical processing in motion extrapolation with rapid forms of visual motion priming and adaptation. *Attention, Perception, Psychophys* 77: 603–612, 2014.

**Battaglini L**, **Campana G**, **Casco C**. Illusory speed is retained in memory during invisible motion. *Iperception* 4: 180–191, 2013.

**Baurès R**, **Hecht H**. The effect of body posture on long-range time-to-contact estimation. *Perception* 40: 674–681, 2011.

**Baurès R**, **Oberfeld D**, **Hecht H**. Judging the contact-times of multiple objects: Evidence for asymmetric interference. *Acta Psychol (Amst)* 134: 363–71, 2010.

**Baurès R**, **Oberfeld D**, **Hecht H**. Temporal-range estimation of multiple objects: Evidence for an early bottleneck. *Acta Psychol (Amst)* 137: 76–82, 2011.

**Baurès R**, **Oberfeld D**, **Tournier I**, **Hecht H**, **Cavallo V**. Arrival-time judgments on multiple-lane streets: The failure to ignore irrelevant traffic. *Accid Anal Prev* 65: 72–84, 2014.

**Benguigui N**, **Ripoll H**, **Broderick MP**. Time-to-contact estimation of accelerated stimuli is based on first-order information. *J Exp Psychol Hum Percept Perform* 29: 1083–101, 2003.

**Bennett SJ**, **Baurès R**, **Hecht H**, **Benguigui N**. Eye movements influence estimation of time-to-contact in prediction motion. *Exp Brain Res* 206: 399–407, 2010a.

**Bennett SJ**, **Orban de Xivry J-J**, **Lefèvre P**, **Barnes GR**. Oculomotor prediction of accelerative target motion during occlusion: long-term and short-term effects. *Exp Brain Res* 204: 493–504, 2010b.

**Bosco G**, **Monache SD**, **Gravano S**, **Indovina I**, **La Scaleia B**, **Maffei V**, **Zago M**, **Lacquaniti F**. Filling gaps in visual motion for target capture. *Front Integr Neurosci* 9: 1–17, 2015.

**Brainard DH**. The Psychophysics Toolbox. *Spat Vis* 10: 433–436, 1997.

**Gilden D**, **Blake R**, **Hurst G**. Neural adaptation of imaginary visual motion. *Cogn. Psychol.* 28: 1–16, 1995.

**Kleiner M**, **Brainard D**, **Pelli D**. What’s new in Psychtoolbox-3? *Perception* 36, 2007.

**De Lucia PR**, **Liddell GW**. Cognitive Motion Extrapolation and Cognitive Clocking in Prediction Motion Tasks [Online]. *J Exp Psychol Hum Percept Perform* 24: 901–14, 1998. http://www.ncbi.nlm.nih.gov/pubmed/9627424.

**De Lucia PR**, **Tresilian JR**, **Meyer LE**. Geometrical illusions can affect time-to-contact estimation and mimed prehension. *J Exp Psychol Hum Percept Perform* 26: 552–567, 2000.

**Lyon DR**, **Waag WL**. Time course of visual extrapolation accuracy. *Acta Psychol (Amst)* 89: 239–260, 1995.

**Makin ADJ**, **Poliakoff E**. Do common systems control eye movements and motion extrapolation? *Q J Exp Psychol (Hove)* 64: 1327–1343, 2011.

**Nakamoto H**, **Mori S**, **Ikudome S**, **Unenaka S**, **Imanaka K**. Effects of sport expertise on representational momentum during timing control. *Attention, Perception, Psychophys* 77: 961–971, 2015.

**Oberfeld D**, **Hecht H**. Effects of a moving distractor object on time-to-contact judgments. *J Exp Psychol Hum Percept Perform* 34: 605–23, 2008.

**Oldfield RC**. The assessment and analysis of handedness: the Edinburgh inventory. [Online]. *Neuropsychologia* 9: 97–113, 1971. http://www.ncbi.nlm.nih.gov/pubmed/5146491.

**Pelli DG**. The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spat. Vis.* 10: 437–442, 1997.

**Peterken C**, **Brown B**, **Bowman K**. Predicting the future position of a moving target. *Perception* 20: 5–16, 1991.

**Rosenbaum D a**. Perception and extrapolation of velocity and acceleration [Online]. *J Exp Psychol Hum Percept Perform* 1: 395–403, 1975. http://www.ncbi.nlm.nih.gov/pubmed/1185126.

**Sokolov A**, **Pavlova M**. Timing accuracy in motion extrapolation: Reverse effects of target size and visible extent of motion at low and high speeds. *Perception* 32: 699–706, 2003.

**Yakimoff N**, **Bocheva N**, **Mitrani L**. A linear model for the response time in motion prediction. *Acta Neurobiol Exp (Wars)* 47: 55–62, 1987.

**Yakimoff N**, **Mateeff S**, **Ehrenstein WH**, **Hohnsbein J**. Motion Extrapolation Performance: A Linear Model Approach. *Hum Factors* 35: 501–510, 1993.

**Zago M**, **Iosa M**, **Maffei V**, **Lacquaniti F**. Extrapolation of vertical target motion through a brief visual occlusion. *Exp Brain Res* 201: 365–84, 2010.

## FOOTNOTES

[(1)]Though response errors are shown in Figure 2, we refer to the time of the response in relation to the actual TTC for ease of understanding. Response times are the sum of the occlusion period and the response error.